TERAHERTZ CHIRPER FOR THE BUNCH COMPRESSION OF ULTRA-LOW EMITTANCE BEAMS*

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Abstract

Recent efforts have demonstrated the possibility of achieving ultralow transverse emittance beams for high brightness light sources and free electron lasers, on the order of tens to hundreds of nanometers [1]. While these lower emittances should translate to improved lasing efficiency and higher peak brightness in FELs, these beams are commensurately more vulnerable to coherent synchrotron radiation (CSR) for the selfsame reasons. Conserving these ultralow emittances through the bunch compressors in an FEL given their increased propensity to emit CSR is particularly challenging. We investigate the possibility of imposing a large energy chirp at terahertz wavelengths to reduce the required magnetic fields in the compressor, counteracting the ultralow emittance in the generation of CSR. A second, higher frequency THz chirper would then be used to dechirp the beam after the chicane. Operation at THz as opposed to conventional radiofrequencies offers significantly larger chirp for similar input powers while still acting on the entire bunch for typical FEL bunch lengths of tens of femtoseconds. Potential experimental schemes will be suggested in the context of LCLS and their feasibility evaluated.

INTRODUCTION AND MOTIVATION

Chicanes are commonly used in the compression of highly relativistic beams. The bunch energy is chirped prior to entry into the chicane where dispersion in the dipoles results in an energy dependent path length. The path length relative to the reference particle is given by Eq.(1), where δ is the relative energy spread and the compression factor, R_{56} is defined in Eq.(2).

$$\Delta s = R_{56}\delta + O(\delta^2) \tag{1}$$

$$R_{56} \approx -2\theta^2 a \tag{2}$$

The bending angle of the magnet, θ, and the distance between dipoles, a, are defined in the schematic in Fig. 1. The relative CSR-Induced horizontal emittance growth in a symmetric 4-Dipole chicane is given by Eq.(3) for small bending angles, $\theta \ll 1$ and a CS parameter, $\alpha_x \approx 0$ between dipoles 3 and 4 [1].

$$\frac{\Delta\epsilon}{\epsilon_0} \approx \frac{\beta(\theta\sigma_{\delta,\mathrm{CSR}})^2}{2\epsilon_0} = 0.12\frac{\beta\theta^4 r_e^4 N^2 R^{\frac{2}{3}}}{\epsilon_0\gamma^2\sigma_z^{\frac{8}{3}}} \tag{3}$$

This emittance growth can be a limiting factor in the compression of ultra-low emittance beams ($\epsilon_0 < 100$nm), of

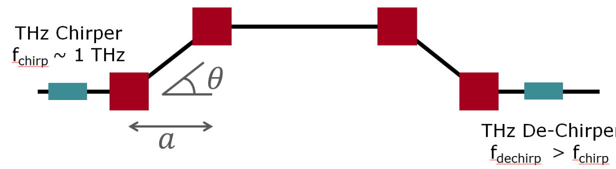

Figure 1: Schematic of a 4 dipole chicane with THz chirping and dechirping.

interest for the next generation of light sources and free electron lasers. While various schemes have been suggested to mitigate this issue [2–4], a simple approach to limiting horizontal emittance growth is to reduce the bending angle, θ. However, to maintain the necessary bunch compression, the time dependent energy spread imparted to the beam prior to the chicane must then be increased. This requires prohibitively high power when using conventional RF technology ($f < 20$ GHz).

We investigated the possibility of using a multi-cycle THz pulse to chirp the beam. At THz frequencies (0.5–1.5 THz), a larger fraction of the RF cycle is sampled by the beam, increasing the chirping efficiency for similar peak fields. The chirper set-up we envision is outlined in Fig. 2.

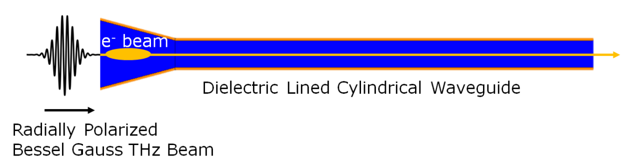

Figure 2: THz chirper using a dielectric lined cylindrical waveguide

A radially polarized Bessel Gauss THz beam couples to the TM_{01} mode in the waveguide, co-propagating with an electron beam. The longitudinal electric field excited interacts with the electron beam, producing a time dependent chirp at the zero-crossing. The compressed beam could then be de-chirped by a second THz waveguide at a higher frequency ($f_{\mathrm{dechirp}} = \frac{\Delta s_{\mathrm{initial}}}{\Delta s_{\mathrm{final}}} f_{\mathrm{chirp}}$) or through a passive dechirper.

WAVEGUIDE DESIGN

The dielectric lined waveguide was optimized for maximum chirp at a given THz pulse energy and the general design is depicted in Fig. 3. R_{inner} was optimized to balance longer interaction lengths with higher on-axis field intensities. R_{outer} was designed to ensure the center frequency of the pulse was synchronous with a 4 GHz electron beam.

As R_{inner} increases, the cutoff frequency drops and the group velocity at the center frequency approaches the speed

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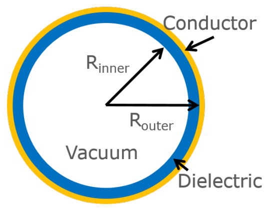

Figure 3: Cross-sectional view of the dielectric waveguide with design parameters labeled.

of the electron, increasing the interaction length. Conversely, the on-axis fields decrease for same input pulse energy as the cross sectional area grows. This tradeoff results in maximum chirp at an intermediate value of R_{inner}, as is demonstrated in Fig. 4.

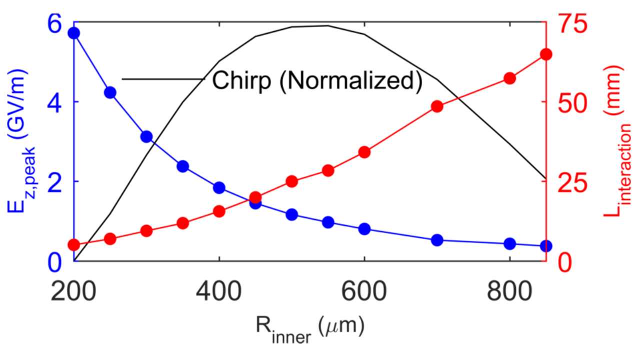

Figure 4: Optimization of R_{inner}. The black line shows a maximum chirp at 550 µm for a transform limited pulse centered at 500 GHz with 50 GHz bandwidth (arbitrary scale).

Other parameters that were varied included the pulse center frequency and bandwidth, and the relative permittivity of the dielectric, ϵ_r. Higher center frequencies resulted in larger chirp, partially due to increased interaction length and peak fields, but largely due to the larger section of the RF period sampled. For a 200 fs electron beam (our test case), the chirp became too non-linear after 1.5 THz so we were limited to this. Narrower pulse bandwidths increased the chirp, as would be expected given the design was optimized for the center frequency, such that other frequencies would not be quite synchronous with the beam. The bandwidths selected for this analysis were 100 GHz at 1.5 THz and 50 GHz at 0.5 THz. Finally, decreasing ϵ_r increases the group velocity and hence the interaction length at relatively little cost to the peak electric fields. However, as ϵ_r decreases, the optimal R_{inner} also decreases, and eventually the beam aperture is small enough that wakefields become an issue. $\epsilon_r = 1.10$ was used for the design study at 1 THz, and $\epsilon_r = 4.41$ at 0.5 THz.

THz BEAM PROPERTIES AND COUPLING

Coupling a free space mode into a TM_{0n} mode can be challenging. However, it has been demonstrated that radially polarized Bessel-Gauss beams couple well into TM modes in the far field [5]. These beams are annular, with a null on axis and can be produced in the lab using a spatial light modulator, a spiral phase plate and a radial polarization converter [6]. The parameters that define the spatial profile of the beam and its propagation characteristics are outlined in Fig. 5.

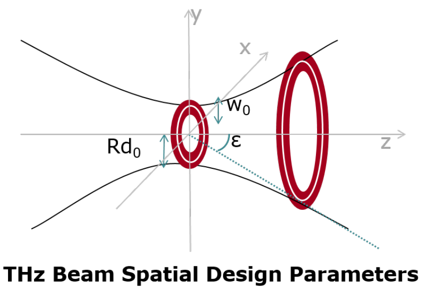

Figure 5: Relevant parameters defining the spatial profile of our Bessel-Gauss beam

A dieletric lined conical horn is used to impedance match at the entrance of the waveguide. The transmission of TM_{01} from the entrance of the horn to the main interaction region was >95% over the entire bandwidth and is not a concern.

The spatial THz beam properties can be optimized for maximal mode overlap between the THz fields and the TM_{01} mode at the exit of the horn. The full optimization is not complete but we have already found a parameter set that achieves 75% coupling efficiency (see Fig. 6 for an idea of how the efficiency varies as a function of the beam parameters defined in Fig. 5). We expect this could be improved with modifications to the horn.

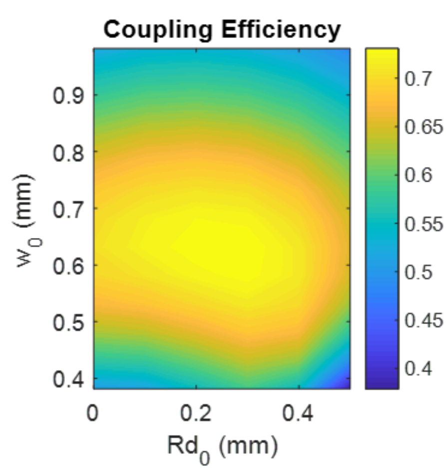

Figure 6: Coupling efficiency at z=1 mm from the waist as a function of waist size, w_0 and initial radius, Rd_0.

BEAM DYNAMICS AND PRELIMINARY RESULTS

The initial optimization was done through an analytical treatment of the interaction between the beam and the fields. The dispersion curve was calculated for a given waveguide geometry. The theoretical fields could then be solved as a function of frequency and the longitudinal wavenumber in the waveguide, β (obtained from dispersion curve (see Fig. 7)). The longitudinal E field calculated is then normalized to the power spectrum of a pulse with a given energy. Here we assume 100% coupling efficiency into the structure, but will replace this with the expected coupling efficiency once the coupling optimization is complete.

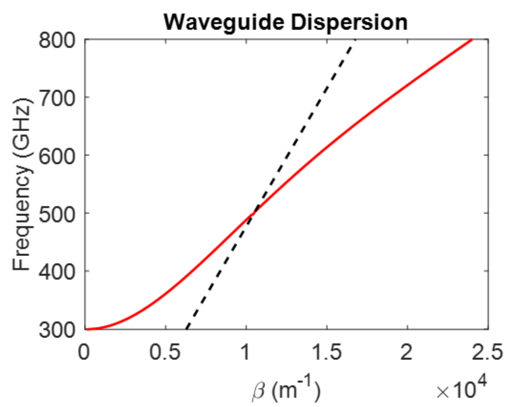

Figure 7: Dispersion curve for a sample geometry and a THz pulse centered at 500 GHz (dashed black line is $\beta = c$).

Dielectric losses were accounted for with the model $P(z) = P_0 e^{-\delta\beta z}$ where δ is the loss tangent of the dielectric. It is particularly important to account for the losses as they affect not only the peak fields, but also the interaction length and thus the optimal inner radius.

After the fields were calculated, the beam wave interaction could be estimated assuming only longitudinal motion and the 1D electron trajectory solved. During this step, the phase of the THz fields and the electron injection time were optimized to achieve maximal chirp (see Fig. 8).

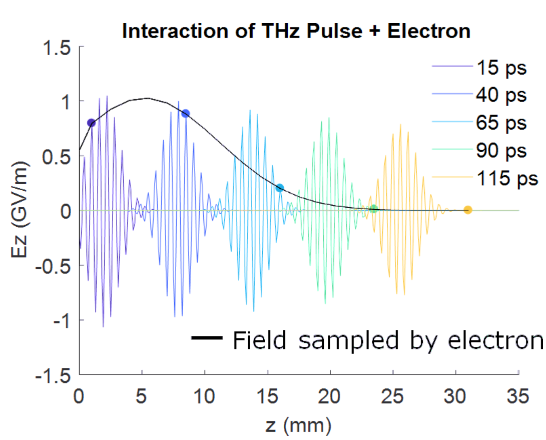

Figure 8: Superposition of the THz pulse E_z field and the electron at various points in time. Note the electron velocity is greater than the group velocity of the wave so eventually overtakes the pulse.

Finally, General Particle Tracer was used to confirm the analytical estimates and model the full beam dynamics [3]. For a set-up similar to LCLS (4 GHz, 200 fs beam), we found a design capable of producing a total chirp across the beam of 112.4 MeV for a 10 mJ THz pulse energy. The design parameters are given in Table 1 (see Fig. 9).

Table 1: Optimal Design Parameters

Parameter	Value	Unit
Center Frequency	1.5	THz
Bandwidth	0.1	THz
R_{inner}	100	µm
R_{outer}	253	µm
ϵ_r	1.1	–
Loss Tangent	2e-5	–
Electron Energy	4	GHz
Beam Length	200	fs

CONCLUSION

A THz chirper was designed and optimized for maximal chirp of a 200 fs, 4 GHz beam. We sought to asses the feasability of such a chirper for use in a bunch compression scheme where the beam is chirped, compressed in a chicane, and de-chirped afterwards.

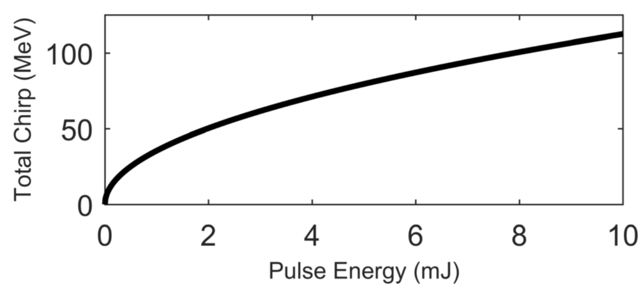

Figure 9: Total chirp as a function of THz pulse energy for the design parameters listed in Table 1.

At 10 mJ of THz, a 112.4 MeV chirp is obtained over the 200 fs beam (± 56.2 MeV), corresponding to $\delta = 2.8\%$ (± 1.4%). The required R_{56} to compress the beam at this chirp is approximately 2.1 mm as opposed to an R_{56} of around 25 mm, as is used in similar situations currently. This suggests one could reduce the CSR induced emittance growth in the compressor by over two orders of magnitude.

Obtaining 10 mJ of THz is pushing the state of the art in THz sources. However even with 1mJ of THz, which has been demonstrated [7], a chirp of 35.6 MeV is achievable, corresponding to an R_{56} of 6.75 and a 13.4x reduction in the emittance growth.

The preliminary results suggest the idea could be worth investigating further. Future work would involve a more in depth analysis of the beam dynamics in the waveguide, particularly in respect to wakefields, optimizing the horn and the spatial profile of the THz beam for efficient coupling and tapering the waveguide to improve the interaction efficiency with wider bandwidth pulses.

ISBN 978-3-95450-182-3

REFERENCES

[1] D. Mitri, "CSR-Induced Emittance Growth and Related Design Strategies," USPAS Lecture, Rutgers University, USA, June, 2015.

[2] P. Emma *et al.*, "Longitudinal pulse shaping for the suppression of coherent synchrotron radiation-induced emittance growth," *Phys. Rev. ST Accel. Beams*, vol. 16, no. 6, p. 060703, Jun., 2013.

[3] D. Stratakis, "Emittance preservation during bunch compression with a magnetized beam," C-A/AP, Upton, NY, USA, C-A/AP/544, Sep. 2015.

[4] D.Z. Khan and T.O. Raubenheimer, "LCLS-II Bunch Compressor Study: 5-Bend Chicane," in *Proc. 36th Int. Free Electron Laser Conf. (FEL2014)*, Basel, Switzerland, August 2015, paper THP027, pp. 755–762.

[5] E. Nanni *et al.*, "Terahertz-driven linear electron acceleration," *Nat. Commun.*, vol. 6, p. 8486, Oct., 2015.

[6] G. Wu, F. Wang, and Y. Cai, "Generation and self-healing of a radially polarized Bessel-Gauss beam," *Phys. Rev. A*, vol. 89, no. 4 p. 043807, April., 2014.

[7] C. Vicario *et al.*, "Generation of 0.9-mJ THz pulses in DSTMS pumped by a Cr:Mg2SiO4 laser," *Opt. Lett.*, vol. 39, no. 23 p. 6632, 2014.